High-efficiency microwave and millimeter-wave electro-optical modulation with whispering-gallery resonators

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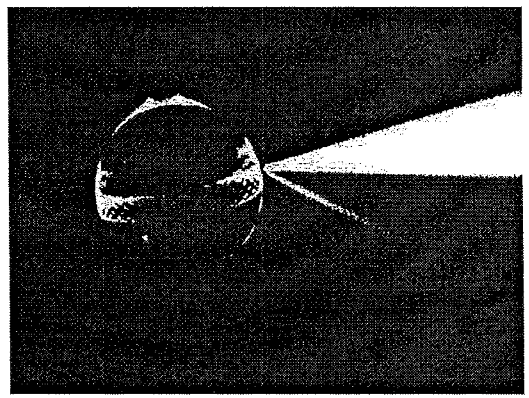
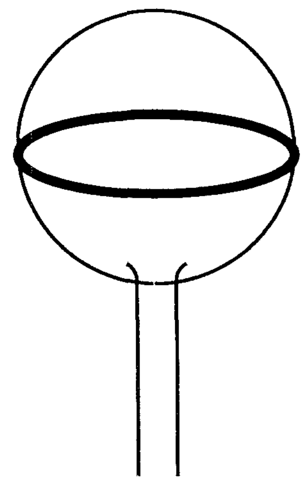


Microspheres have been here

low material loss (transparent material)

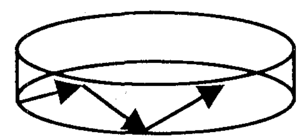
low bending loss (high-contrast boundary)

LOW SCATTERING LOSS (TIR always under grazing incidence) $\Theta \to \pi/2$; compare to disks/ rings:



$$\frac{I_R}{I_I} = e^{-\left(\frac{4\pi\sigma}{\lambda}\cos\Theta\right)^2}$$ (J.W.S.Rayleigh)

EVEN WITH MOLECULAR ROUGHNESS σ, ONLY CURVATURE CONFINEMENT ALLOWS **Q** LIMITED BY MATERIAL ATTENUATION:

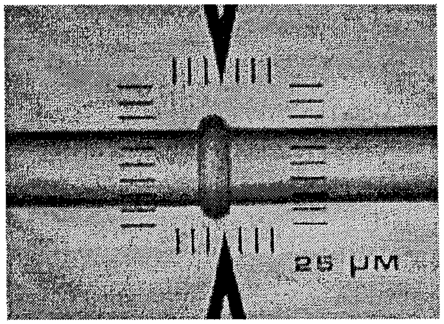


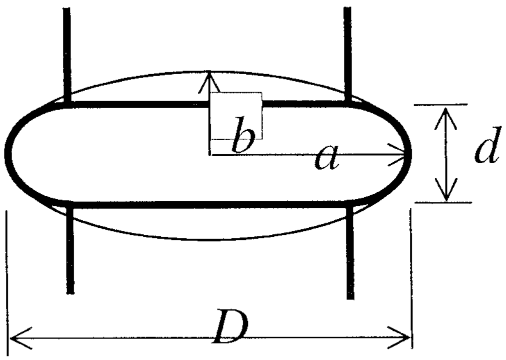
10^8 -10^{10} in silica spheres vs. 10^3 - 10^5 in microrings !!

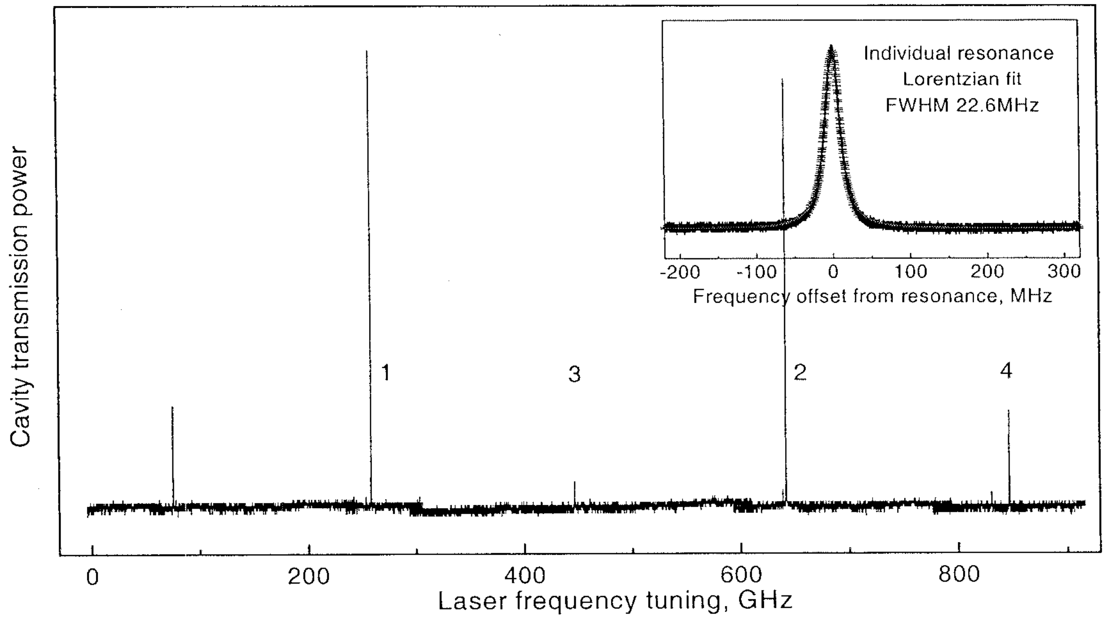
(Drawback: "quite many modes" compared to planar rings)

Novel geometry, a highly oblate spheroid, or microtorus:

much less modes

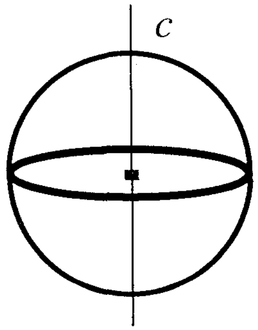






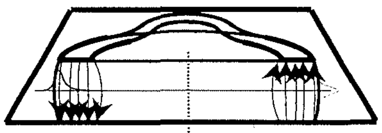
Near the symmetry plane (at the location of WG modes), toroidal surface of outer diameter D and cross-section diameter d coincides with that of the osculating oblate spheroid with large semiaxis $a = D/2$ and small semiaxis $b = \frac{1}{2}\sqrt{Dd}$

Electro-optic modulation with whispering-gallery modes



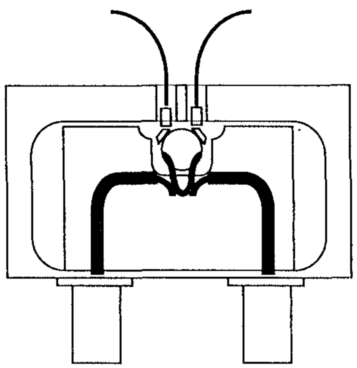
Optical whispering-gallery modes in lithium niobate sphere (torus) in the perpendicular plane to principal crystal axis.

Optical FSR is the operational microwave frequency



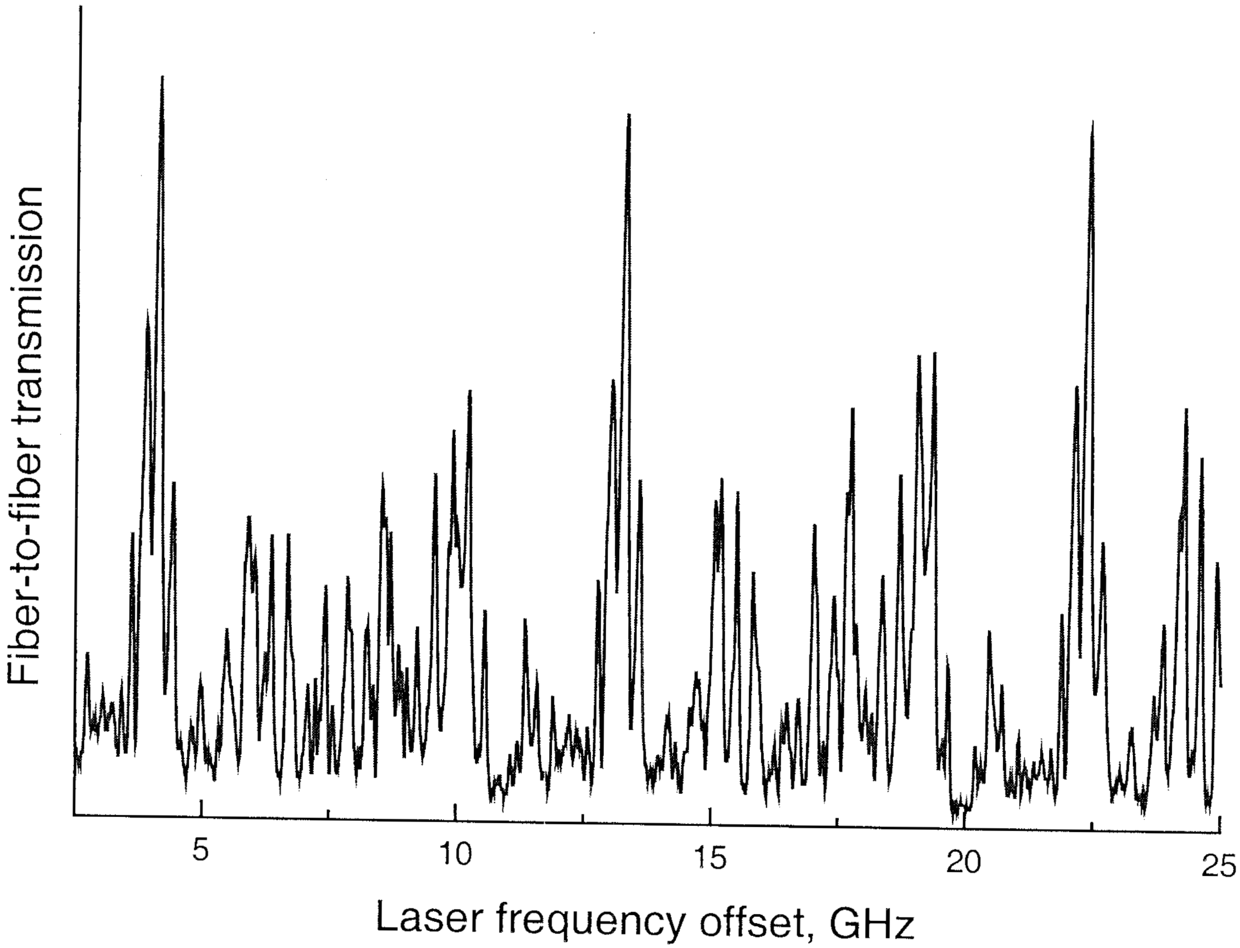
Equatorial layer is sliced out of the sphere (torus) and microwave cavity(ies) is (are) built around.

Variation of microwave field phase along the circumference is required to satisfy momentum conservation in 3 photon process by $\chi^{(2)}$



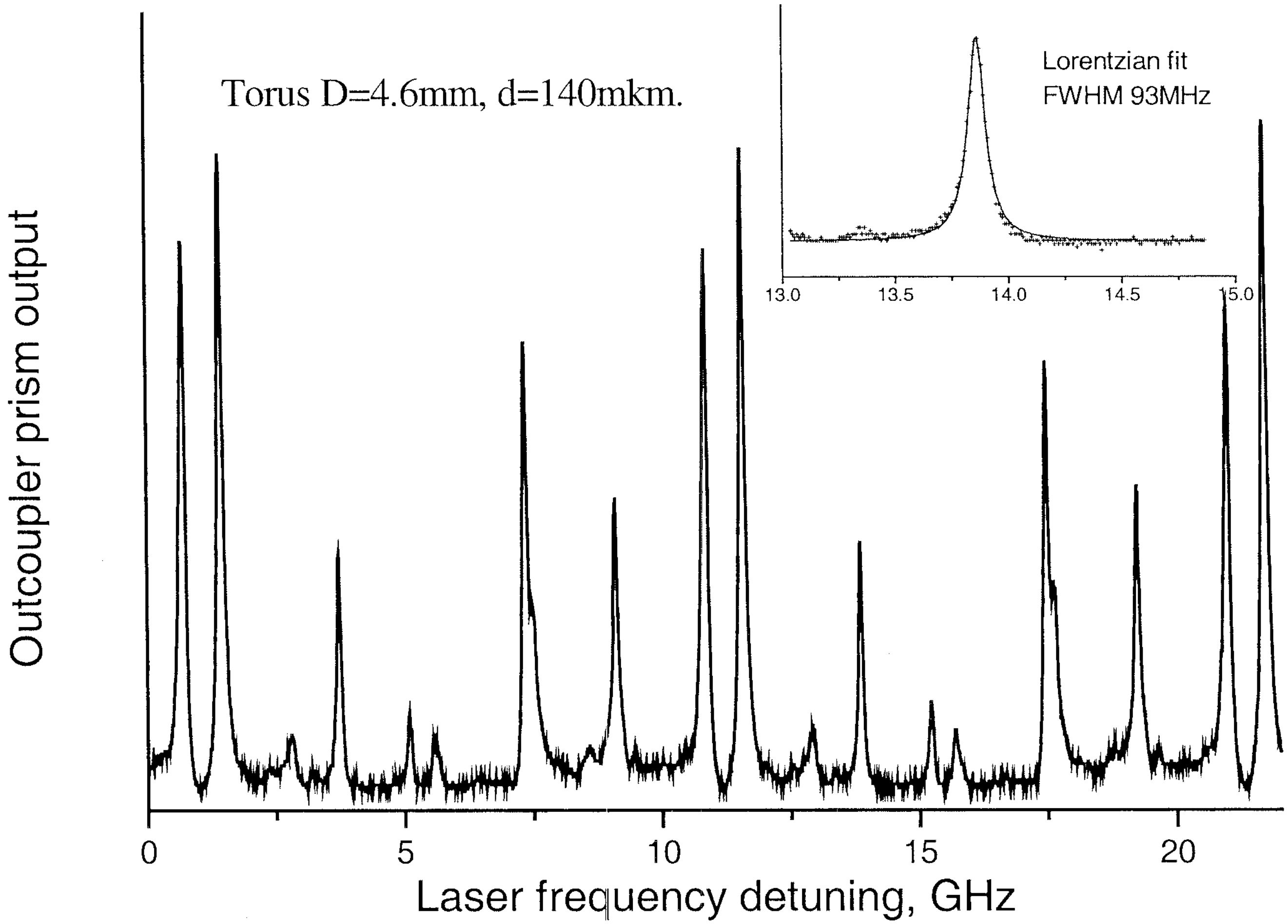
The setup is completed with microwave coupler(s), one or two optical coupling prisms, and fiber collimators

Optical spectrum of *spherical* lithium niobate resonator D = 4.8mm



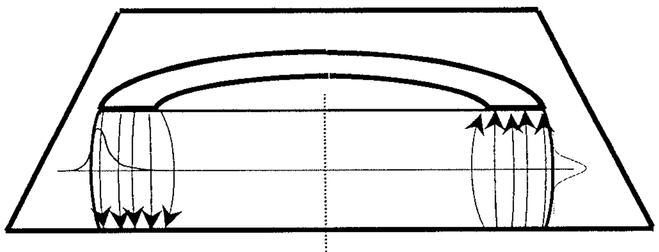
Optical spectrum of *toroidal* lithium niobate resonator D = 4.6mm, d = 140mkm

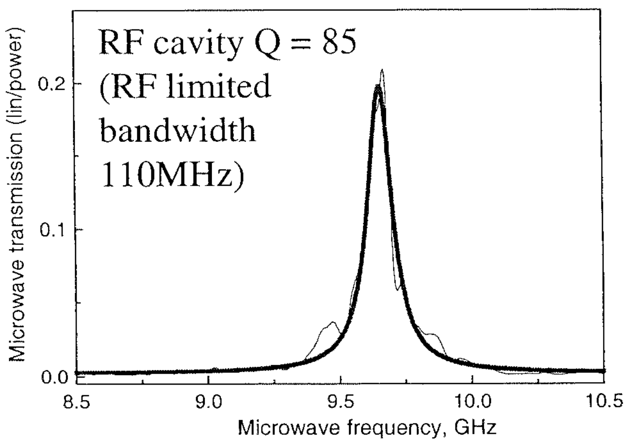
Loaded optical quality-factor Q ~ 2 x 10 ^{6}

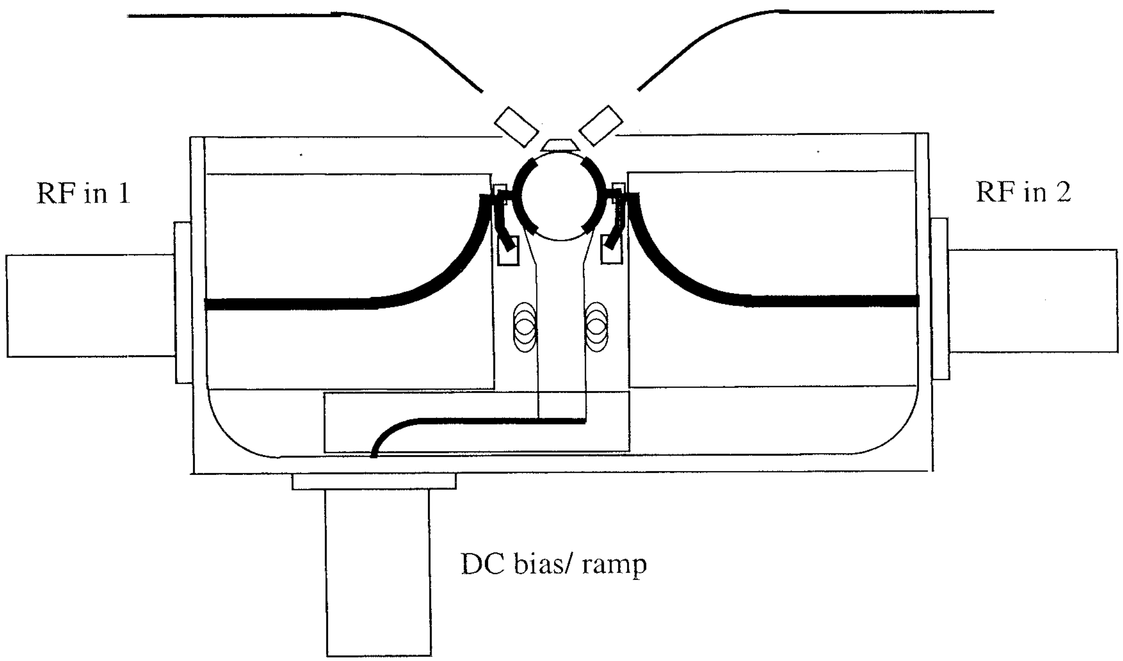


Schematic of optical and microwave mode overlap, microwave resonance, and example of embodiment

Operation of WG resonance modulator: high-Q optical whispering-gallery modes superimposed with mm-wave microstrip cavity

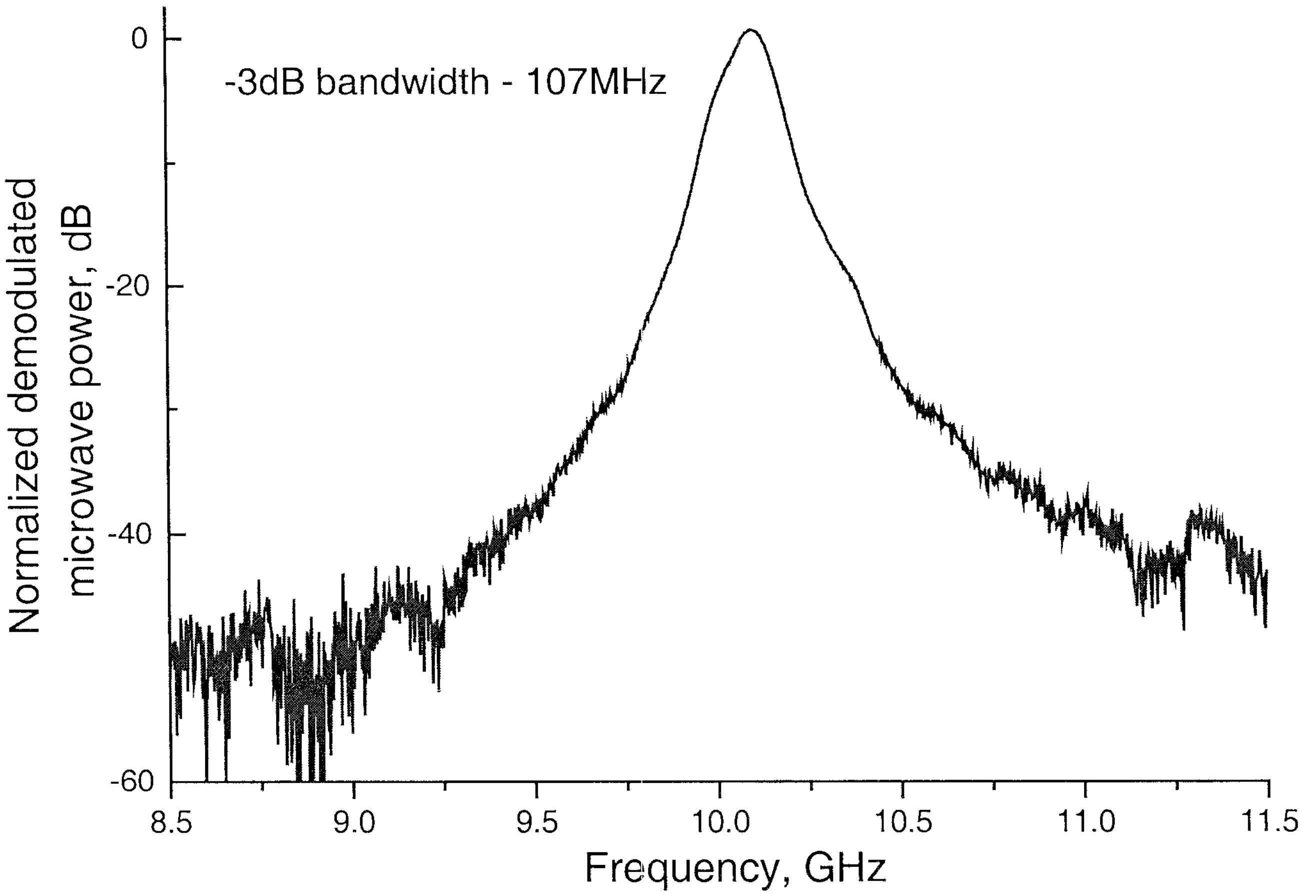




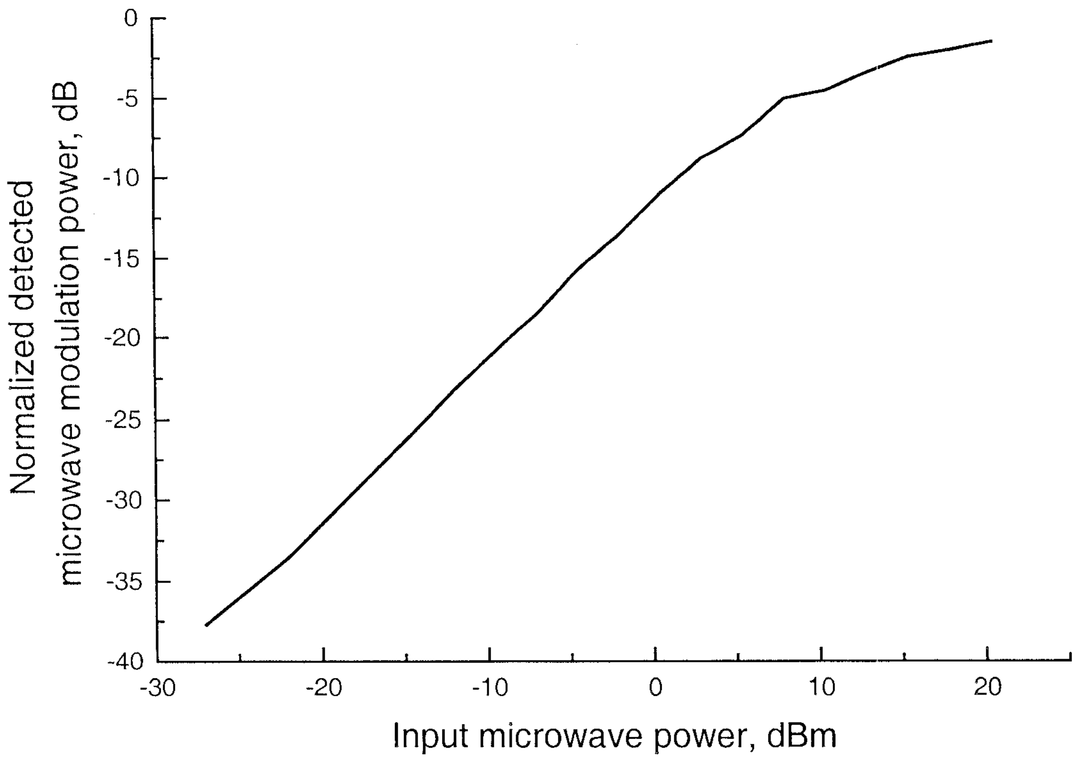


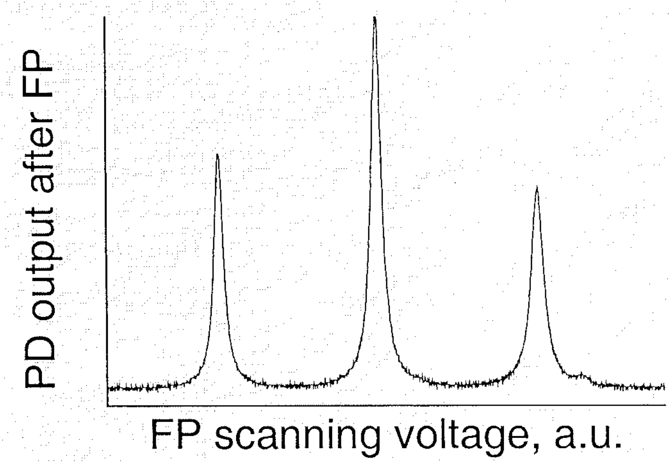
Frequency response

of the X-band prototype with 4.6mm x 140μm toroidal resonator



Power characteristic and optical spectrum of output signal of the X-band prototype with 4.6mm x 140μm toroidal resonator





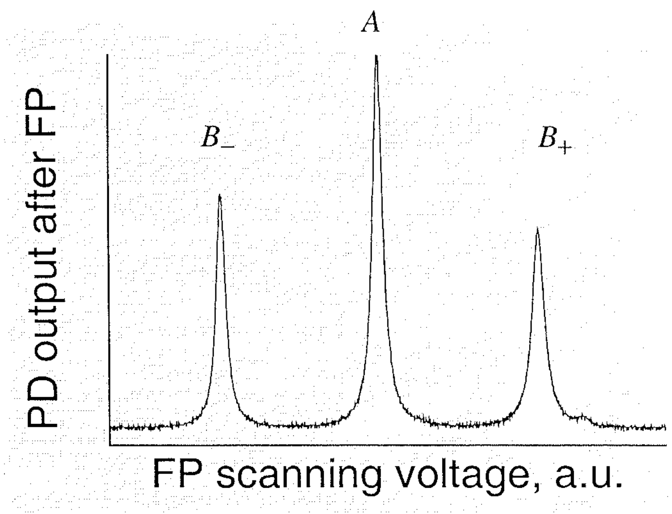
Basic equations

$$\dot{A} = -\gamma A - ig(B\_C + C^{+}B_{+}) + F_A$$

$$\dot{B}\_ = -\gamma B\_ - igC^{+}A$$

$$\dot{B}_{+} = -\gamma B_{+} - igCA$$

$$\dot{C} = -\gamma_M C - ig(B_{-}^{+}A + A^{+}B_{+}) + F_M$$



Steady state solution

$$\frac{W_{\pm}}{W_{in}} = \left(\frac{2S}{1+2S^2}\right)^2, \quad \frac{W_0}{W_{in}} = \left(\frac{1-2S^2}{1+2S^2}\right)^2$$

$$S = \frac{4gQ}{\omega}\sqrt{\frac{W_M Q_M}{\hbar\omega_M^2}}$$

Coupling constant

$$g = \frac{\omega}{2}\chi^{(2)}\sqrt{\frac{4\pi\hbar\omega_M}{V_M}}\left[\frac{1}{V}\int_V dV\Psi_A\Psi_B\Psi_C\right]$$

The modulation is maximal when $2S^2 = 1$

$$\Rightarrow \quad W_M = \frac{1}{2}\left(\frac{\omega}{4gQ}\right)^2 \frac{\hbar\omega_M^2}{Q_M}$$

Current experiment:

$$\omega_M = 2\pi \times 10\ GHz,$$
$$\chi^{(2)} = 3\times 10^{-11}\ m/V,$$
$$V_M = 10^{-4}\ cm^3,$$
$$Q_M = 100,$$
$$Q = 2\times 10^6$$
$$g = 2\pi \times 100 Hz$$

Maximum modulation at W_M~10 mW

Perspectives:

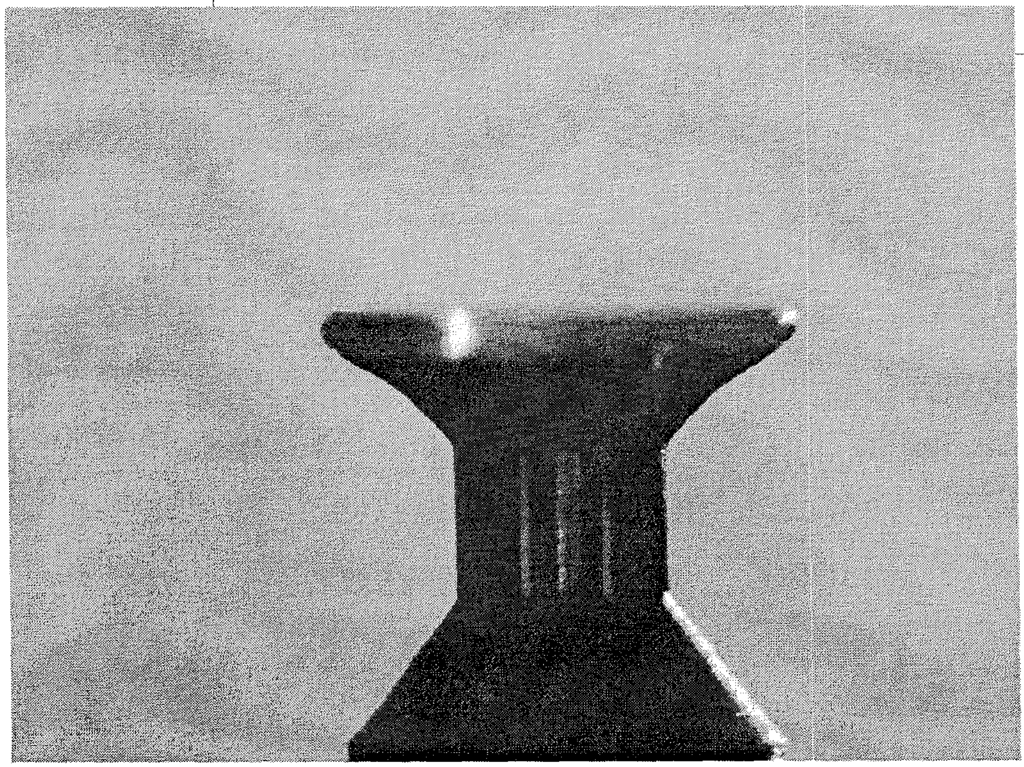
$$\omega_M = 2\pi \times 40\ GHz,$$
$$V_M = 10^{-6}\ cm^3,$$
$$Q_M = 10^3,$$
$$Q = 10^7$$
$$g = 2\pi \times 500 Hz$$

Maximum modulation expected at W_M~ 10μW

1. Low power modulator;
2. Microwave receiver

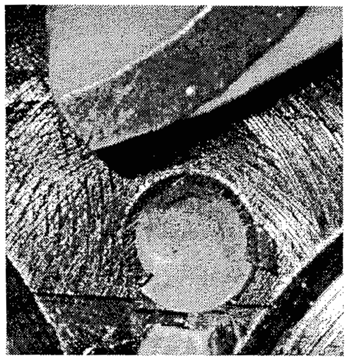
!

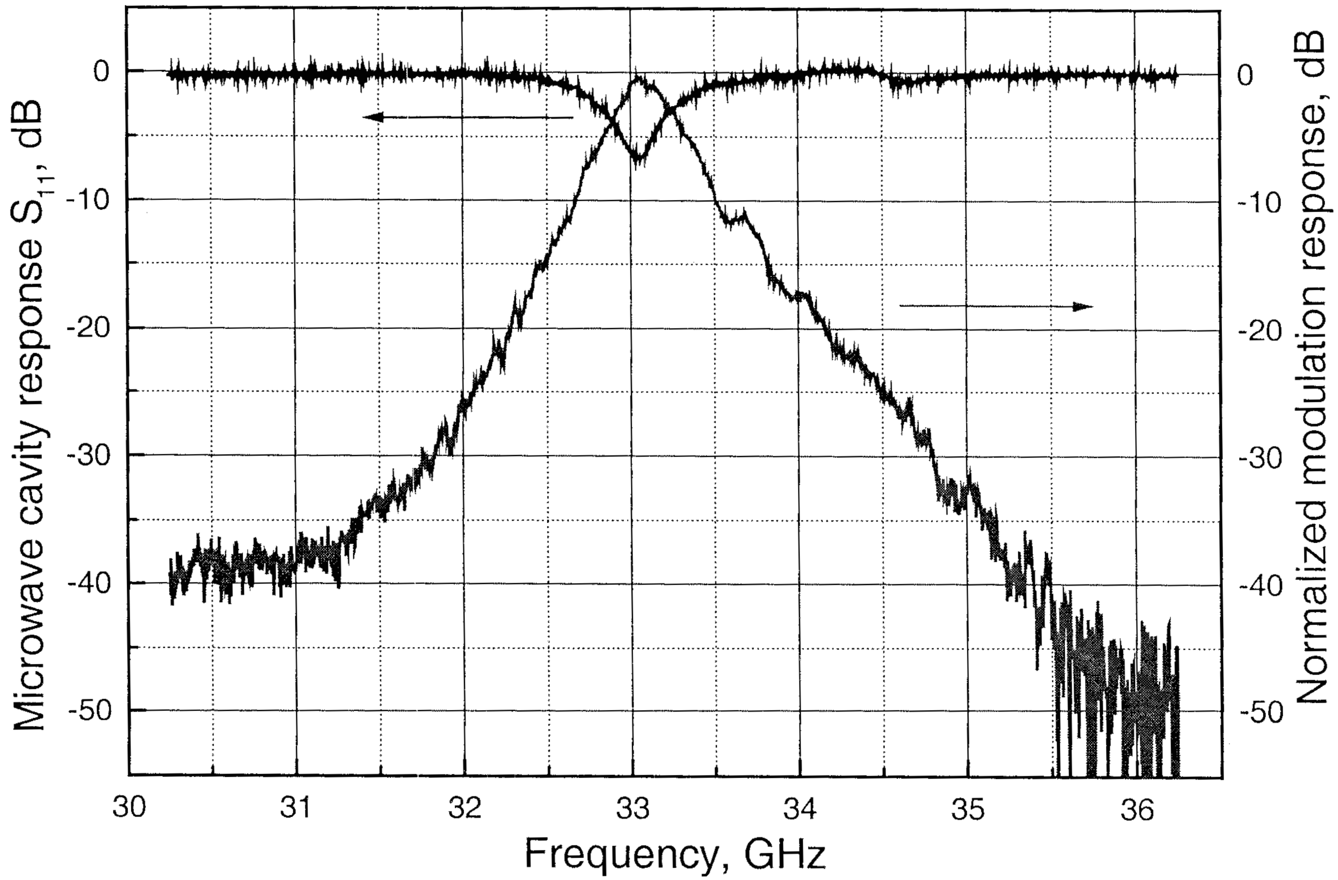
Preliminary Results on $LiNbO_3$ Toroidal Whispering-Gallery Resonators for Ka Band Electro-Optical Modulation:



Diameter 1.45mm,
Thickness 110micron,
Transverse curvature radius 65micron,
Optical Q ~ 10^6,
Optical FSR 33GHz

Frequency response of the Ka band $LiNbO_3$ whispering-gallery mode electrooptical modulator.

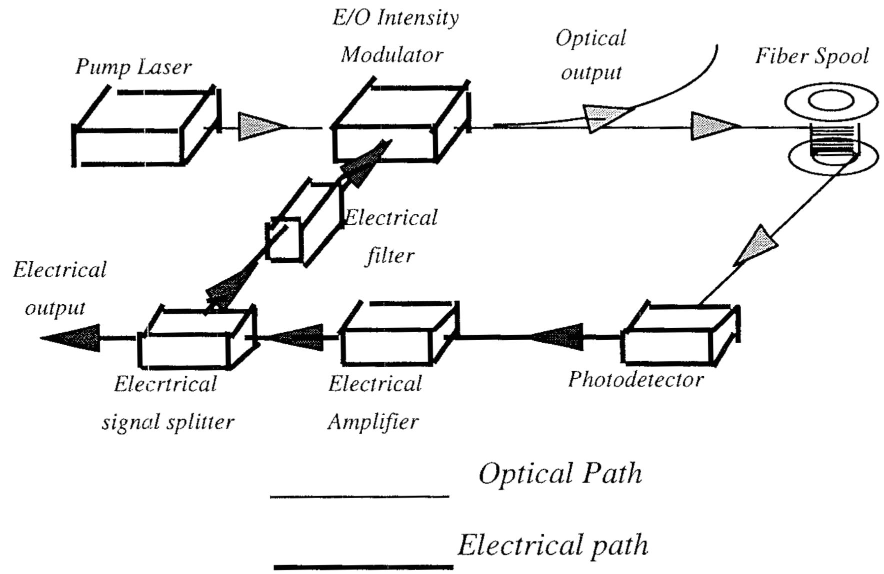




Example of applications: fully photonic OEO

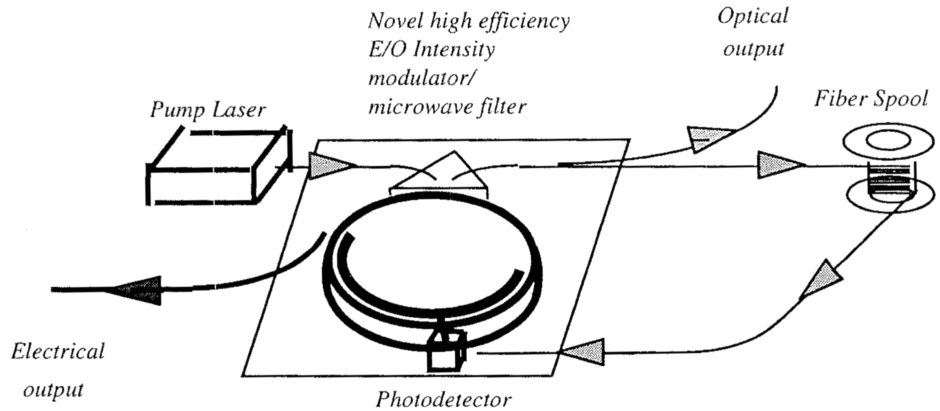
1. Conventional OEO:

low efficiency conventional modulator requires electrical amplification for oscillation

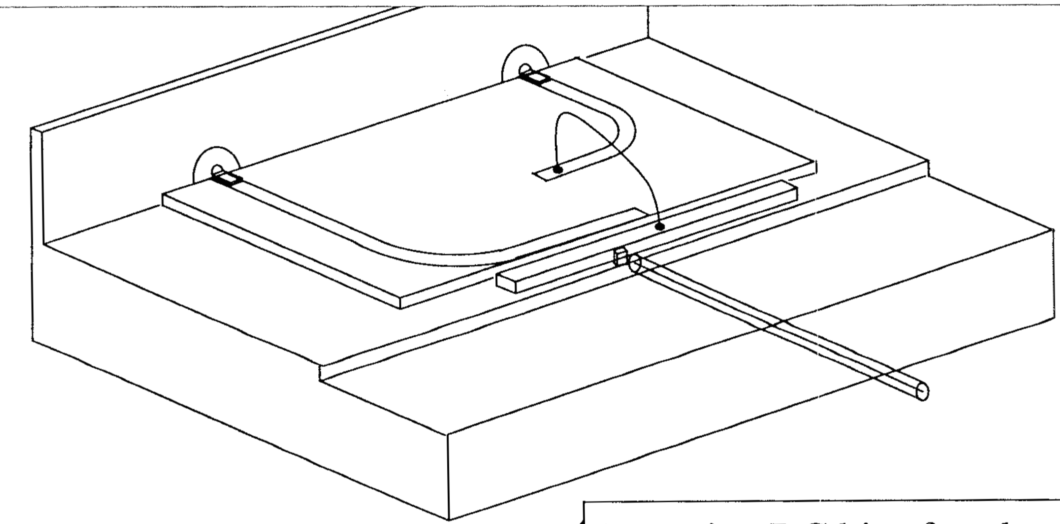


2. Novel OEO:

fully photonic (without RF amplifier) with high-efficiency $LiNbO_3$ resonance modulator integrated with photodetector chip



Impedance matching for all-optical-pumping OEO

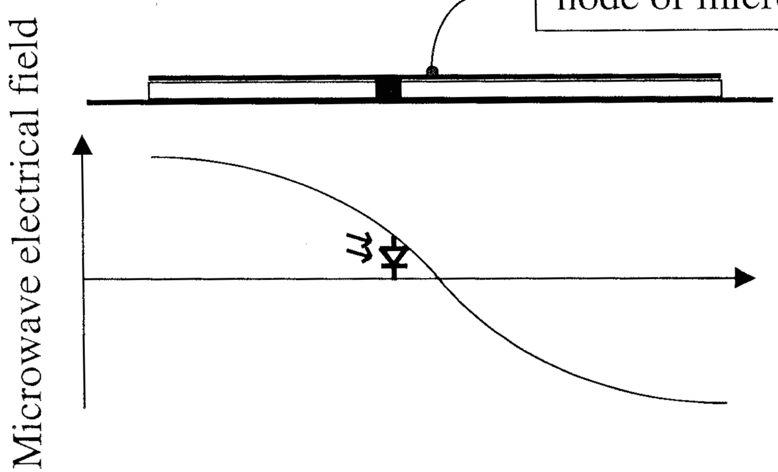


A concept of direct optical feeding of electro-optic modulator via

resonance impedance matching of high-speed photodiode with $\lambda/2$ microstrip cavity on $LiNbO_3$ WG modulator

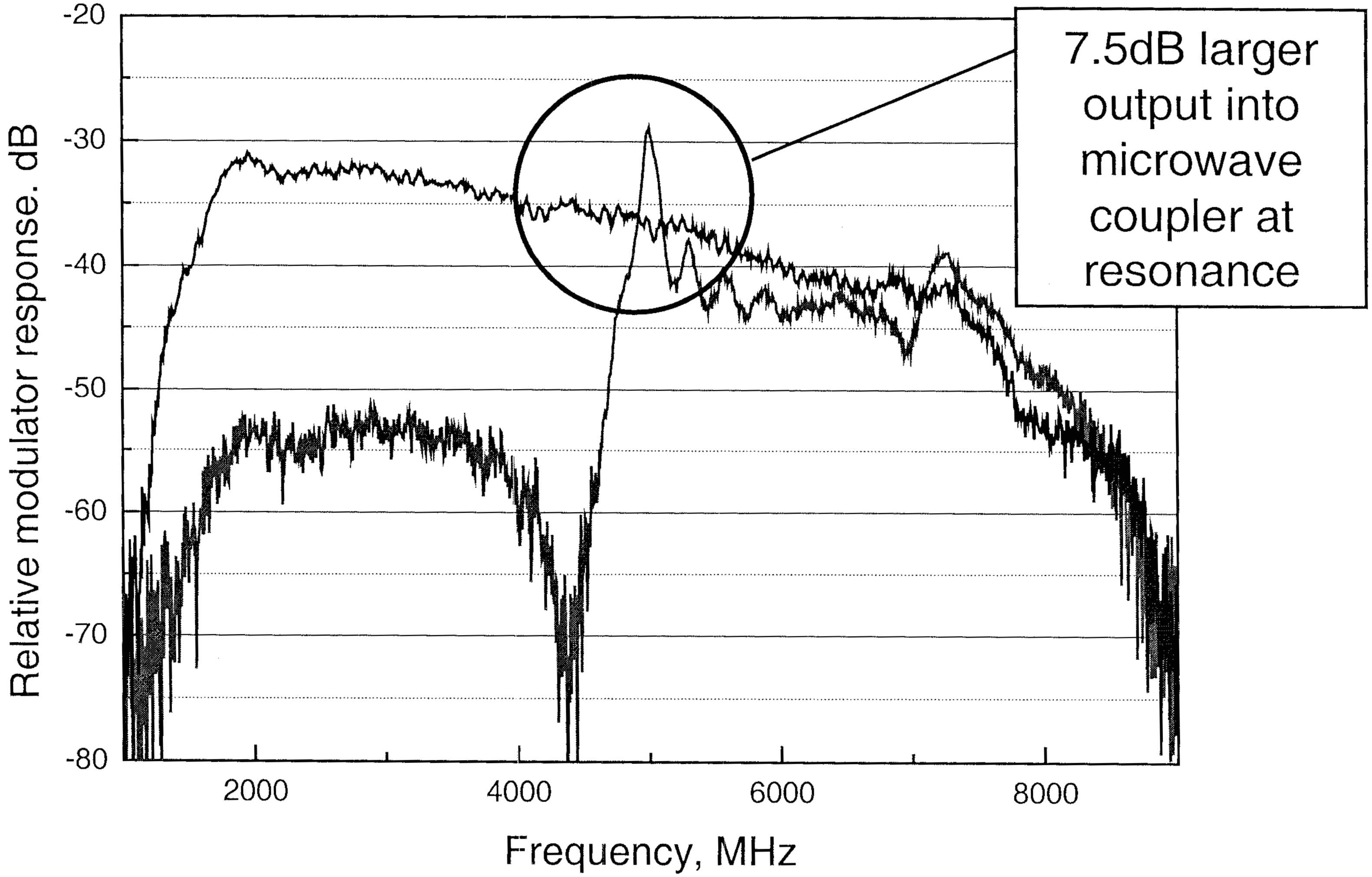
Preliminary experiment with PD excitation of C-band microstrip cavity

Negative DC bias for photodiode via high-inductance wire bond at a node of microwave field



Sub-mount 20GHz InGaAs photodiode with impedance ~1kOhm feeds the microstrip cavity via parallel connection at an adjustable point to provide regime of resonance voltage transformer. Cavity Q~100 corresponds to the resonance impedance ~5kOhm at ~10GHz

Performance of resonance photodiode compared to packaged 50 Ohm fiber pigtailed module Fermionics FS-30



Electro-optic modulation with whispering-gallery modes: CONCLUSION

- Optical losses in lithium niobate allow for high-Q (up to 10^{7}) WG modes. High finesse translates into potential of strong reduction of controlling electrical power compared to zero-order interferometers such as MZ

- RF driving power can be further reduced by matching microwave cavity that can be as high-Q as 10^{3} (limited by dielectric loss)

- Limited band, non-power-hungry modulators (1mW and less is feasible) may be useful for mm-wave applications such as low-rate data, fiber radio & picocellular com, as well as in novel optoelectronic oscillators